Glass Sensors - A European Study to Estimate the Effectiveness of Protective Glazings at Different Cathedrals

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Summary

A new integrating method for monitoring the intricate environmental conditions for stained glass windows and their protective glazings is offered by glass sensors based on low durable potassium-calcium silicate glasses with a high sensitivity against corrosive stresses. The easy-to-handle technique is able to detect the combined impact of climatic stresses, pollution, and microbiological effects as well as synergetic interactions. Due to the sensitivity of the glass sensor, judgements about corrosive stresses and further damage risks can be made within a few months. The corrosion progress of the sensors is determined by infrared spectroscopy and checked by microscopy. Various types of protective glazings at different cathedrals in seven European countries have been investigated. The first results indicate that internally ventilated protective glazings have a higher protective effect than externally ventilated or nonventilated systems. The nonventilated type of protective glazing even raised the corrosive stresses for the stained glass windows.

Résumé

Une nouvelle méthode d'étude des conditions environnementales complexes des vitraux protégés par des verrières extérieures, est proposée à l'aide de plaquettes de verre. Ces plaquettes sont réalisées avec des verres de silicates de potassium et de calcium de courte durée de vie, leur sensibilité envers les stress corrosifs étant très élevée. Leur facilité de mise en œuvre permet de rendre compte des stress climatiques, de la pollution, des effets microbiologiques et des interactions synergiques. Grâce à la sensibilité de ces plaquettes, nous pouvons estimer au bout de quelques mois l'intensité des stress corrosifs et des dommages qui en découleront. Les progrès de la corrosion sur les plaquettes sont analysés à l'aide de la spectroscopie infra-rouge et de la microscopie. De nombreux types de verrières extérieures de différentes cathédrales européennes ont été étudiés. Les premiers résultats ont montré que les verrières pourvues d'une ventilation intérieure sont mieux protégées que celles qui possèdent une ventilation extérieure. Les plus mauvais résultats sont obtenus pour des vitraux dont la verrière n'est pas aérée.

Keywords
Conservation, Stained Glass Windows, Protective Glazing, Model Glass, Environment, Glass Sensors.

1. Introduction

Medieval stained glass windows belong to the most important cultural heritage of Europe. Within the last decades, however, a disastrous deterioration took place: the wonderful stained glass windows and their glass paintings as pieces of art are acutely menaced by environmental corrosive influences. A widely accepted protection measure for stained glass windows is protective glazings. Although many different types of external protective glazings are installed throughout Europe, there is very little information available from which to guage their real effectiveness and there are no standards for new installations. A survey of temperature and humidity itself is not sufficient because the progress of glass corrosion is also influenced by noxious gases, dust and air, microorganisms as well as synergetic interactions. The very intricate corrosive impacts which work in front of and behind the protective glazings depend on the location of the object and on construction details of the glazing, e. g. the type of ventilation, size and location of ventilation slots, and distance of the panels.

Up to now the knowledge about the precise connection between these influences and the resulting impact on the material as well as the synergistic effects among them is fragmentary. To cope with these limitations, an alternative and integrating concept, a low cost and easy-to-handle technique is asked for. Highly sensitive potassium-lime silicate glasses (so-called glass sensors) show a low durability against corrosive stresses and therefore can be used as an integrating method for detecting the environmental effects on cultural property.

The glass sensors can deliver results within short observation times (after a few months) and a useful comparison of different objects and situations is possible.

In this respect, the aim of an international glass sensor study (supported by the Comité Technique of the Corpus Vitrearum Medii Aevi) was to take stock of the efficacy of different types of protective glazings at the following locations:

country	*object*
Austria	Stefansdom, Vienna
	Magdalenenkirche, Judenburg
	Wallfahrtskirche, Straβengel
	Stadtpfarrkirche, Friesach
Austria	Stift, Heiligendreuz
Switzerland	Klosterkirche, Königsfelden
	Kreuzgang, Wettingen
	Stadtkirche, Kappel
	Groβmünster, Zürich
	Klosterkirche, Hauterive
The Netherlands	St. Jans, Gouda
	Herr, Kerk, De Rijp
Germany	Dom, Erfurt
	St. Dionys, Esslingen

2. Glass Sensor Method

The glass sensor method [1-4] is based on very sensitive potassium-lime silicate glasses as a dosimeter material. The surface of the glass sensors interact with their environment causing alterations in the surface layer. This can be registered quantitatively by infrared spectroscopy (IR) and semiquantitatively by microscopy.

The corrosive progress is registered quantitatively by IR absorption measurements. The difference in intensity (ΔE) of a suitable OH absorption band of a sample before and after exposition corresponds directly to the degree of corrosion of the sensor. The two major corrosion effects, the leached gel layer and the increasing crystalline corrosion crust (K-Ca sulfate hydrates) cause this increase in the intensity of the OH absorption band. This means high ΔE values stand for high corrosive levels. Additional microscopical investigations allow qualitative and semiquantitative estimation about the degree of corrosion, too.

Two different types of sensors are employed: MI (extremely sensitive, specially designed for indoor conditions) and MIII (less sensitive, specially designed for outdoor conditions). The sensors are small (5x5 cm^2 of size), easy-to-handle and of low costs. They can be fixed on the windows without interfering in the aesthetics of the objects of art. An exposure time of 12 months is chosen to include all the seasonal effects like heating periods or rainy periods.

3. Results of the sensor Measurements and Features of the Investigated Objects.

Table 1. *Features of internally ventilated objects*

object	remarks	window	protective glazing	Delta-E 1	Delta-E 2	Delta-E 3	Delta-E 4	type
St. Jans Gouda (NL)	marine area, city center with heavy traffic heated church	S	1905 * on top/bottom** 2cm slots 5-6cm distance***	0,04 0,015	0,025 0,01		0,21 0,025	III
Herr. Kerk De Rijp (NL)	marine area, rural low traffic very humid inside church	S 11	1989 on top/bottom 1cm slots 4cm distance	0,05 0,02	0,02 0,02*		0,17 0,025	III
St. Dionys Esslingen (D)	industrial area heavy traffic heated church	S c8	1978 3,5x4,5cm slots 5cm distance	0,025	0,025		0,135	I III
		N b8		0,02 0,02*	0,035 0,005		0,175 0,03	
Klosterkirche Kappel am Albis (CH)	rural area sometimes heated church	s VII	1986 on bottom 1cm slot 3,5cm distance	0,015 0,005	0,02 0,01		0,1 0,045	III
		n VI	1950 only few mm slots on top 1.5cm distance	0,025 0,015	0,015 0,015		0,18* 0,045*	
St. Bartimä Friesach (CH)	rural area heavy traffic non heated church	nII 4a	1978/79 on top: tilted on bottom: 7cm high slots 7cm distance	0,015 0,005	0,02 0,02	0,02 0,03*	0,155 0,02	III
Brunnenhaus Heiligenkreuz (A)	rural area extremly humid (through fountain) non heated church	N IV 1c	1987 on top: tilted on bottom: 3cm high slots 5cm distance	0,035 0,03	0,02 0,005	0,02 0,015	0,23 0,035	III
Mariendom Erfurt (D)	city center heavy traffic high level of pollution non heated church	sII B10	1982/83 50x5m slots on bottom 5-7cm distance	0,09 0,015	0,145 0,005		>1 0,08	III
		n VI B10	1989 40x5cm slots on bottom 5-7cm distance	0,115 0,02	0,12 0,05		0,605 0,065	III
		n II B10	1981/82 50x5 cm slots on bottom 5-7cm distance	0,1 0,02	0,27 0,035		0,8 0,11	III
Klosterkirche Königsfelden (CH)		S V		0,03 0,015	0,01 0,02		0,07 0,03	III
		Nord LH		0,025 0,015	0,025 0,02		0,125 0,04	I III
Stefansdom Vienna (A)	city center heavy traffic industrial area heated church	s II 4b	1968 on top: tilted on bottom: 7cm high slots 8cm distance	0,035 0,03	0,02 0,015	0,06 0,05	0,15 0,025	III
Magdalenen-kirche Judenburg (A)	industrial area heavy traffic non heated church	s II 4b	1968 on top: tilted on bottom: 7cm high slots 7cm distance	0,03 0,025	0,01 0,1	0,014* 0,01	0,085 0,02	III
Wallfahrts-kirche Straßengel (A)	industrial area non heated church high level of soot	O I 3c	1975 on top: tilted on bottom: 7cm high slots 7cm distance	0,01	0,04			

* : Year of installation
** : Slots at protective glazing
*** : Distance between protective glazing and historic stained glass

Table 2. *Features of nonventilated and externally ventilated objects*
ventilated objects

object	remarks	window	protective glazing	Delta-E 1	Delta-E 2	Delta-E 4	type
Großmünster Zürich (CH)	Industrial area heavy traffic heated church	S X	1970 nonventilated 2cm distance	0,02	>1	0,37	I
				0,005	0,01	0,025	III
		O HId	1970 external ventilation 0.5-1cm slots allover 6cm distance	0,005	0,065	0,065	
				0,01	0,025	0,02	

Table 3. *Features of specially constructed objects*

object	remarks	window	protective glazing	Delta-E 1	Delta-E 2	Delta-E II	Delta-E 3	Delta-E 4	typ
Klosterkirche Hauterive (CH)	rural area heated church	O HI3a	1985 on top and bottom 2-3cm slots. Between historic stained glass and protective glazing an additional glazing see Figure 8 6cm distance	0,015	0,005	0,05	0,04	0,07	I
				0,01	0	0	0,025	0,025	III
Kreuzgang Wettingen (CH)	Industrial area heavy traffic heated church	O XIV b	1989 5cm slots allover 7cm distance additional glazing infront of historic stained glass, see Figure 8	0,075	0,065			0,245	
				0,015	0,045			0,035	

4. Sensor positions

The sensors are normally placed in a medium height of the windows.

Position 1: front side of historic glazing (corresponds to indoor conditions)

Position 2: reverse side of historic glazing (corresponds to interspace conditions)

Position 3: front side of protective glazing

Position 4: reverse side of protective glazing (corresponds to outdoor conditions)

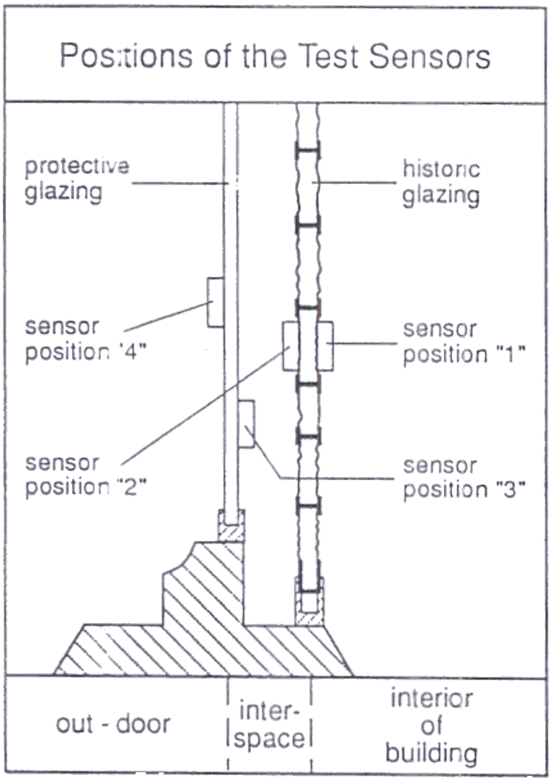


Figure 1: Sensor positions

5. Discussion of the Results

The glass sensor study should deliver data about the environmental stresses working inside and outside of ecclesiastical stained glass windows and about the efficiency of different types of protective glazings installed at the cathedrals.

For this purpose several cathedrals listed in Tables 1, 2, and 3 were equipped with glass sensors. Three mainly different protective glazings are identified:

*protective glazings with an internal ventilation
*protective glazings with an external ventilation
*nonventilated protective glazings.

5.1 *Internally ventilated protective glazings*

The corrosive impacts working on the stained glass windows derive (among other things) from humidity, temperature changes, condensation effects, soot and dust from candle burning, and, of course, from outdoor air quality.

Influence of the outdoor conditions

A typical example of the harsh influence of the local environment is Erfurt where extremely bad conditions prevail for the stained glass windows with regard to all three positions: high corrosive levels at the front and reverse side of the historic windows (positions 1, 2) and on the reverse side of the protective glazing (position 4) have been found. (See also Figure 2 where the ΔE values for all objects are listed in graphic charts.)

Erfurt high air pollution	pos. 1 high stress
	pos. 2 high stress
	pos. 4 high stress

The very special situation of Erfurt is well known: extremely high pollution through unfiltered industrial exhaustive gases and through lignite firing with a high sulfur dioxide emission.

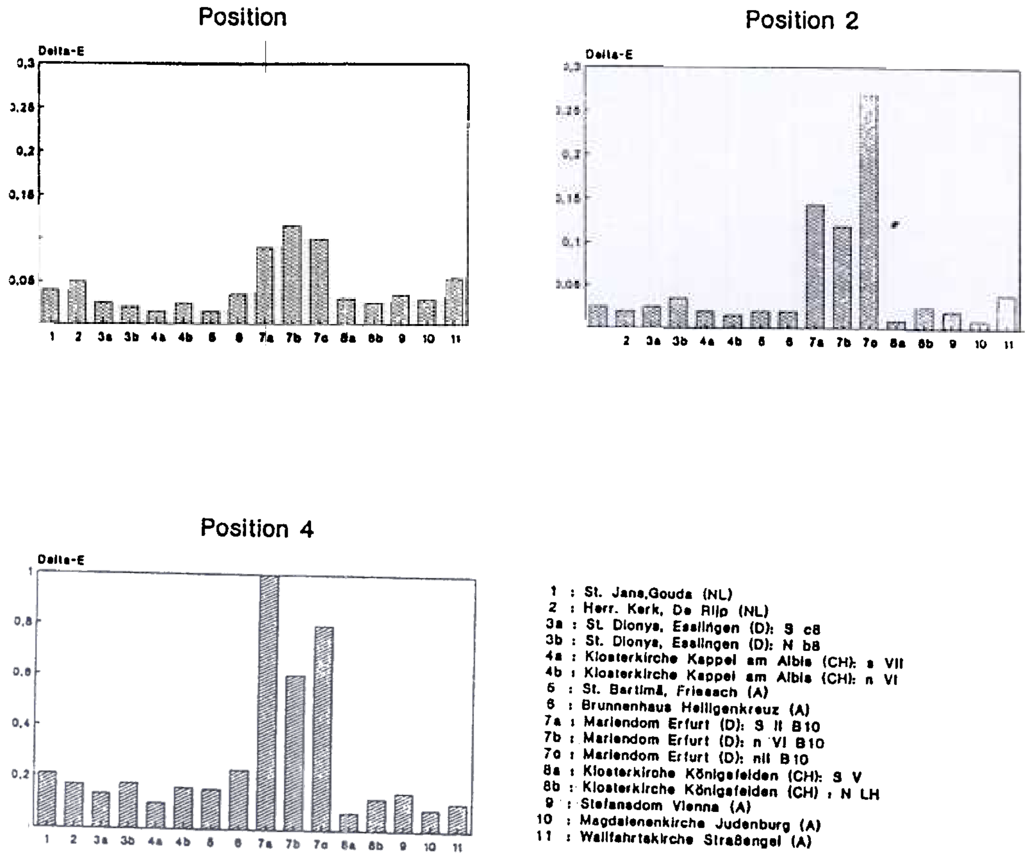


Figure 2: Internally ventilated objects

The situation at the two windows in Kappel am Albis, Switerland, is very different from Erfurt. All ΔE values of the sVII and nVI window at the positions 1, 2, and 4 are very low which is probably due to the unpolluted environment. The church is situated in the highlands and in a rural area without industrial plants and heavy traffic.

Kappel: low air pollution pos. 1 low stress
pos. 2 low stress
pos. 4 low stress

Whereas the preceding results can be explained by the strong effect of air pollution on the corrosion rate of the glass sensors, the following example emphasizes that humidity itself leads to significant corrosive damages on the surfaces of the glass sensors. The pump room of the Zisterzienserstift at Heiligenkreuz, Austria, has a very humid environment and is situated in the rural highlands. The ΔE values (0.230) at the position 4 are relatively high compared to the unfavourable highly polluted area around Erfurt (0.800) or to the heavy traffic situation at St. Jans (0.210) in Gouda, The Netherlands.

Heiligenkreuz low air pollution
pos. 4 high stress
high humidity

Protective effect numbers

For internally ventilated protective glazings the protective effect is contingent upon the indoor environment, a sufficient air circulation, and on the distance between glass panel and outside glazing. To perform assessments of the achieved protective effect so-called "protective effect numbers" may be proposed as a criterion. The protective effect numbers (calculated as [ΔE (position 1) - ΔE (position 2)/ΔE (position 1)] depend on the indoor conditions of each cathedral and on the construction details e. g. the size of ventilation slots. The higher the numbers the better the protective effect. Positive numbers indicate that the corrosive stress level at position 2 (interspace) is lower than at position 1 (indoor stress level). If the stress levels at position 1 and 2 are equal, zero numbers are calculated. Negative numbers stand for a stress level higher at position 2 than at position 1. In this case a revising of the performance of the protective glazing is recommended.

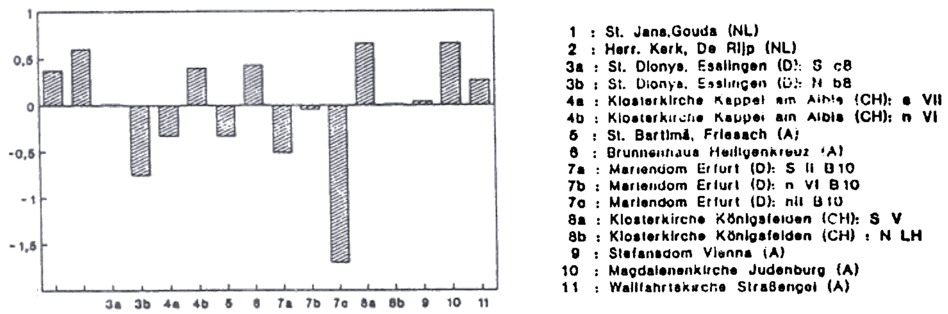


Figure 3: Protective effect numbers of internally ventilated objects

Influence of the protective glazing

The installed glazings at Königsfelden (SV) and Judenburg (sII) have the highest protective effect numbers (0.66, see Figure 3 nos. 8a and 10) indicating the high efficiency of those glazings and a lower corrosive stress at position 2 compared to position 1. Zero protective effect numbers, as found in Esslingen (Sc8) and in Königsfelden (N LH, nos. 3a, 8b) mean that comparable corrosive environments work at positions 1 and 2. Negative protective effect numbers reveal the poor potential of protective glazings as listed in Figure 3. At the three investigated windows in Erfurt the strong influence of special circumstances (like a construction site near a window) on the efficacy of protective glazings can be seen (see Figure 3, nos. 7a-c). The nII and sII windows have very low protective effect numbers (-0.51;-1.7) in contrast to the nVI window (-0.093) although the corrosive stress levels at position 1 are nearly the same for all three windows (ΔE-0.1). The nII window possesses the least efficient protective glazing of all investigated objects due to its special construction of the protective glazing (restricted air circulation through bottom slots, large scale panel with cracks allowing outdoor air exchange). During the exposition time of the sensors, some construction and restoration work inside the church near by the nII window was going on and caused lots of dust and dirt raising also the corrosive attack. A considerable higher efficiency of a protective glazing can be observed at the nVI window, where a revised type of construction was applied: improved air circulation through bottom slots and a very tight geometrically patterned glazing with a lead structure.

5.2 *Nonventilated and externally ventilated protective glazings.*

During the last years the majority of the countries preferred internally ventilated protective glazings. Only few samples of nonventilated and externally ventilated systems exist or will be installed.

The sensor study clearly showed that these constructions have a lower protective effect. For example the results attained from the sensor measurements at the SX window at the Groβmünster Zürich where a nonventilated type was realized, obviously seem to be not encouraging. At position 2, the interspace, an extremely high ΔE value (> 1 !) was found (see Figure 4). This implies that the corrosive stress is significantly risen and is even higher than the outdoor stress. As a consequence, an additional endangering of the stained glass window must be taken into account when protected by a nonventilated system.

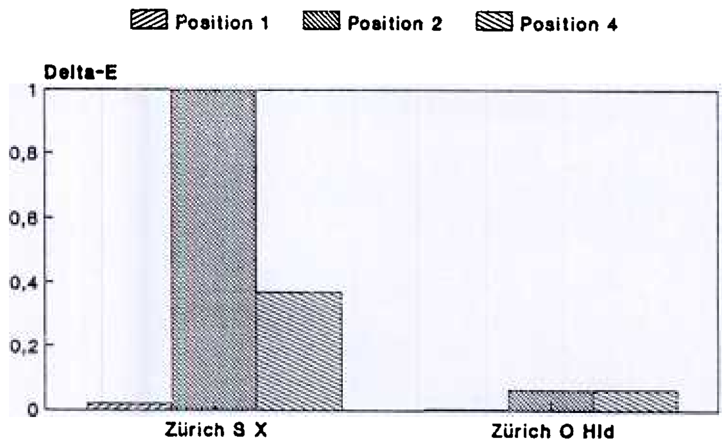


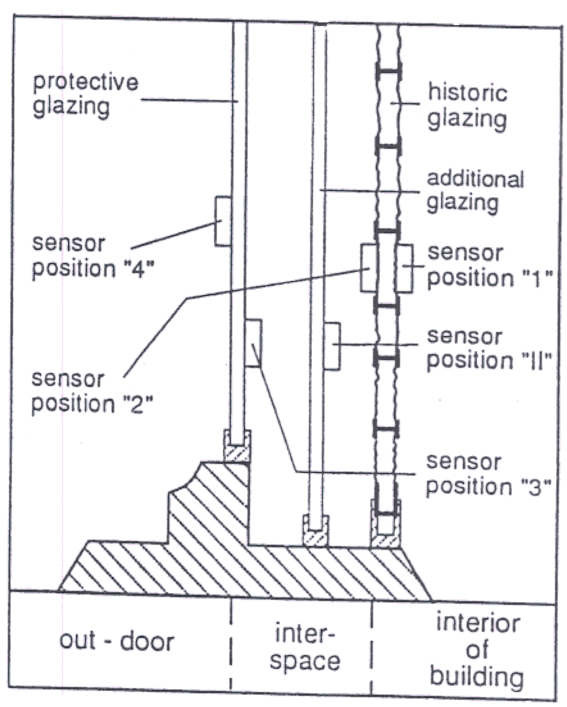
Figure 4: Nonventilated and externally ventilated objects

Not that drastically bad, but still unsatisfactory, is the condition of the historic stained glass window with an externally ventilated protective glazing which was also installed at the Groβmünster in Zürich (O HId). The reverse side of the stained glass is affected by a stress identical to the corrosive environment at the outdoor position (see Figure 4). Under these circumstances the corrosion rate at the original cannot be reduced sufficiently.

5.3 ***Specially constructed objects***

At the Klosterkirche in Hauterive, Switzerland, a specially constructed protective glazing was installed. The features of this protective glazing are given in Figure 5.

Figure 5: Special construction at the Klosterkirche, Hauterive



The ΔE values (see Figure 6) found at the various positions imply that a very good protective effect is obtained with this kind of protective glazing. The corrosive stress levels at the front and the reverse side of the original stained glass window are extremely low whereas the positions II and 3 (additional glazing and protective glazing) are much more corrosively strained. These findings coincide with the frequent condensation noticed at position II and 3. Here the influence of a construction detail is evident and shows that the sensors correspond exactly with the various microclimates occurring at the different positions.

Figure 6: Specially constructed objects

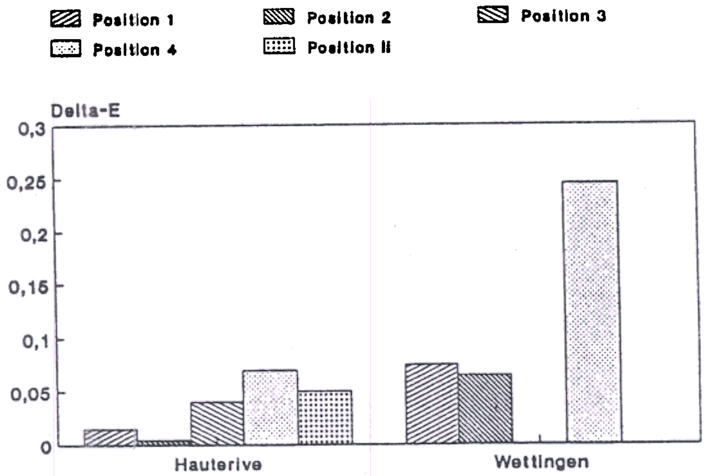
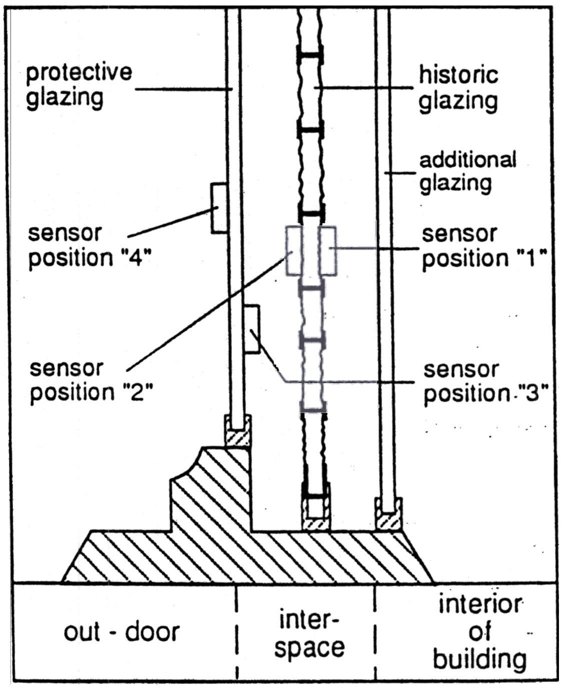


Figure 7: Special construction at the Kreuzgang, Wettingen



The protective glazing installed at the Kreuzgang, Wettingen (see Figure 7), shows an opposite effect. The additional glazing which is fixed in front of the original, leads to condensation at positions 1 and 2 as indicated by the relatively high ΔE values at these sites (see Figure 6). The implications of these results are obvious. This kind of an additional construction detail aggravates the microclimate around the stained glass window and creates more corrosive stress which will lead to further damage for the pieces of art.

6. Conclusions

The information assembled and discussed here provides perspectives on the potential of glass sensor measurements in the field of estimating the corrosive stress levels of stained glass windows. The results showed clearly that the corrosion progress can be reduced best with an internally ventilated type of protective glazing. Although large differences in the protective effect of those types occurred, the data is too sparse to draw definite conclusions about reasons. In the future more detailed sensor studies must be made to ascertain the exact reasons for a high or low protective effect.

Considerations of the very low protective effect of externally ventilated systems indicate that the reverse side of the original is exposed to such corrosive environments from which the pieces of art should be protected. In the case of nonventilated systems the conditions for the stained glass windows are worse that without a protective glazing. This type leads to an enforced endangering of the originals. In contrast to the nonventilated system the protective effect attained with the specially constructed protective glazings at the Klosterkirche, Hauterive, is extremely good. In Figure 8 the protective effects of selected objects are listed. Here the protective effect is calculated as the degree of the reduction of the outdoor stress [(ΔE (position 4) - ΔE (position 2)/ΔE (position 4)]

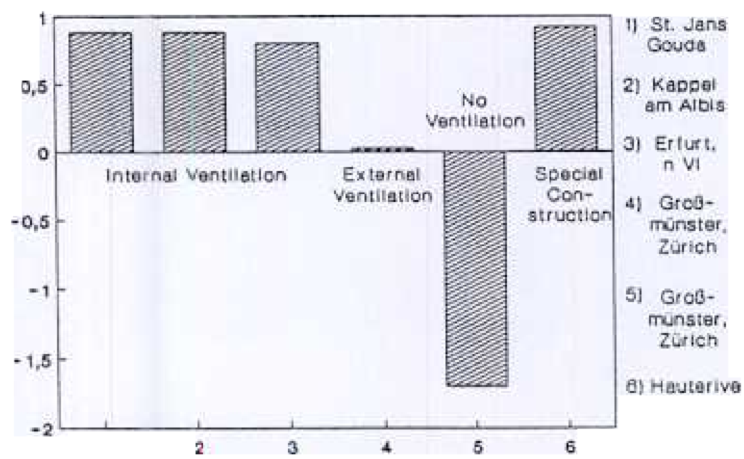


Figure 8: Protective effects of different types of protective glazings

The deterioration of stained glass windows does not only occur on the reverse side but also on the front side due to the indoor environment. Considering the corrosive stress levels found at position 1 (see Figure 2a), it has to be assumed that they are also damaging the original glass and especially the glass paintings.

Thus, the new findings should be considered to be a starting point for further discussions and investigations in the field of conservation of stained glass windows.

7. Acknowledgement

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